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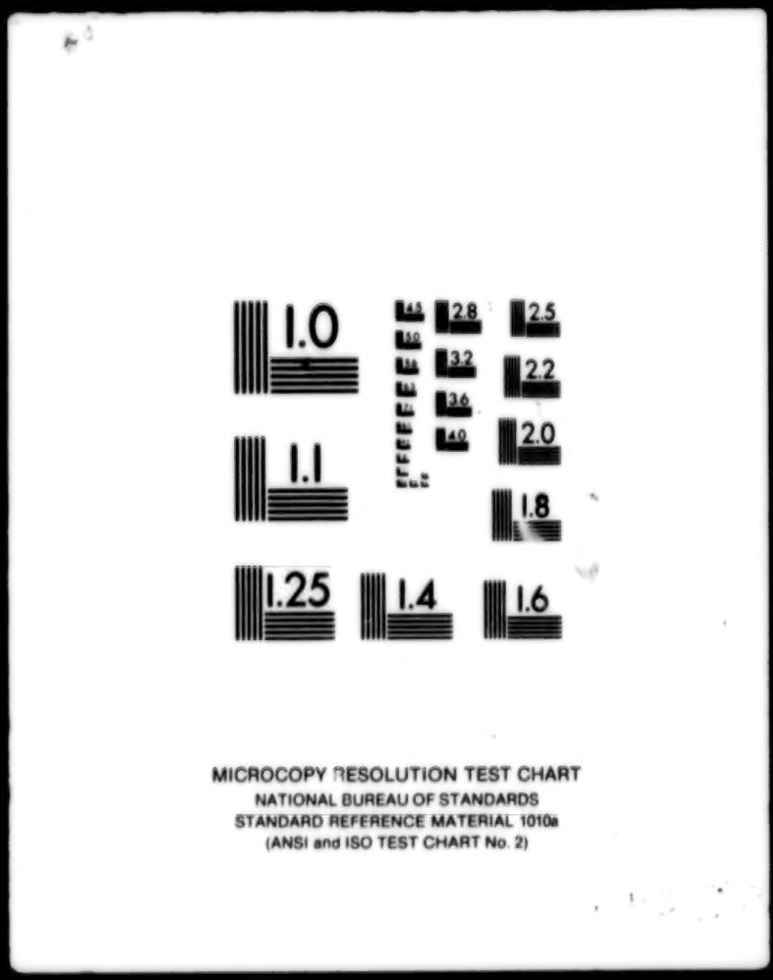

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NASA Special Publication 6104

A Perspective on the Human-Rating Process of U.S. Spacecraft: Both Past and Present

George Zupp, Editor

(NASA-SP-6104) A PERSPECTIVE ON THE HUMAN-RATING PROCESS OF US SPACECRAFT: BOTH PAST AND PRESENT (NASA. Johnson Space Center) 14 p

N95-26586

Unclas

H1/18 0048161

February 1995

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February 1995

Acknowledgments

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This publication is available from the NASA Center for AeroSpace Information, 800 Elkridge Landing Road, Linthicum Heights, MD 21090-2934 (301) 621-0390.

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Preface

The purpose of this report is to characterize the process of "Human-Rating" as employed by NASA for human spaceflight.

An Agency-wide committee was formed in November 1992 to develop a Human-Rating Requirements Definition for Launch Vehicles based on conventional (historical) methods. The committee members were from NASA Headquarters, Marshall Space Flight Center, Kennedy Space Center, Stennis Space Center, and Johnson Space Center (JSC).

After considerable discussion and analysis, committee members concluded that human-rating is the process of satisfying the mutual constraints of cost, schedule, mission performance, and risk while addressing the requirements for human safety, human performance, and human health management and care.

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1. Synopsis

Historically, the methods of *implementing* human-rating vary as a function of program, across the systems and subsystems that are components of a program or project, and sometimes across mission phases within a program. Although details of specific *implementations* have varied, the top-level, fundamental *process* has remained constant. That invariant *process* is as follows:

- The program establishes processes and procedures for human-rating early in the definition phases and constantly reviews these processes and procedures as the program matures.
- Historically, the human-rating process can be collected into three fundamental components: human safety, human performance, and human health management and care.[1]
- The human-rating process evaluates and balances the components of human-rating with cost, schedule, risk, benefit, and performance.

As used here, *human-rating implementation* refers to a specific approach to ensuring that the space system is human-rated. For example, capsule separation and jettison is an implementation approach that provides the required level of human safety during launch. However, an abort system carries risks of malfunction which can affect otherwise normal missions. Quad-redundancy and high reliability are other implementation approaches that can satisfy a required level of human safety.

Similarly, as used here, the *human-rating process* is that set of procedures and methods that not only estimates and evaluates the combined components of human-rating along with cost, schedule, risk, benefit, and performance, but also maintains an active consistency of decisions.

2. Historical Background on Human-Rating

A review of NASA's historical approach to human-rating a space system demonstrates that the *process* has been essentially invariant or constant. However, specific *implementations* vary as a function of the program benefit or return and of the program's systems and subsystems, and across the mission phases. The historical process has been to examine the safety of human spaceflight from a total integrated system viewpoint. The following historical synopsis highlights variations of the specific implementation approaches to human safety.

2.1 Historical Perspective of Human Safety

2.1.1 Implementation Methods Vary as a Function of Program

Mercury and Gemini. The launch vehicles employed on Mercury and Gemini were basically developed to be launched on the Redstone short-range ballistic missile and the Atlas and Titan intercontinental ballistic missiles. Atlas and Titan vehicles were flying operational systems which were basically simple systems with selected redundancy. The central focus of human-rating the integrated vehicles of Mercury/Atlas and Gemini/Titan was to add redundancy and a launch escape system for the crew.

Thus, the task for NASA and the prime contractors was to define the monitoring instrumentation for abort condition sensing and the warning systems to alert both crew and ground to initiate an abort. This approach necessitated a thorough review of all failure history, flight history, and corrective actions to determine lead times before failure and crew warning and resultant action response times to decide on manual versus automatic initiation. Additional redundancy was defined for certain time-critical hardware failures such as rate gyros to sense flight path deviations or vehicle engine failures. Redundant sensors were added to monitor tank pressures, propulsion system pumps and chamber pressure, hydraulic system actuation, and control. Selective hardware screening programs were instituted for critical hardware.

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[1]The human rating process for the Mercury, Gemini, and Apollo Programs was centered on human safety. The Skylab and Shuttle Programs added to this an emphasis on human performance and health management.

In addition, a rigorous ground test and unmanned flight test program was designed to demonstrate the hardware margins and flight performance before actually placing a crew in the launch vehicle. There were 17 flight tests prior to Alan Shepard's flight. Critical design and safety reviews and programs such as manned flight awareness were instituted to ensure compliance with requirements and to increase awareness in all workers that the ultimate use of the vehicle they were building would be to carry humans.

Apollo. For the Apollo Program, there were no existing boosters with the required performance. Therefore, the Saturn IB and V launch vehicles were designed for human flight from the beginning. The designers, beginning in the definition stages, addressed issues such as the classical engine and propulsion system failure modes, the necessary redundancy to be employed, the critical instrumentation sensing and abort warning system requirements, the TNT equivalent yield, fireball size and overpressure envelope that an escape system would have to clear; the warning times required for manual and automatic sensing, and implementation of the crew escape system. Again, the design criteria for structural design of tanks, lines, and components and the certification and acceptance testing was defined and implemented.

The Apollo design for launch vehicles, abort sensing and implementation, and the launch escape system had additional redundancy and safety improvements as compared to the Mercury and Gemini launch vehicles. Note that redundancy is not in itself sufficiently more reliable but rather depends on the method(s) of implementation. Also, redundancy is not feasible for all subsystems.

There was an extensive ground and unmanned flight test program to validate the design features and to certify the launch escape system since the launch vehicle was uniquely developed for the Apollo mission. Similarly, there were extensive design and safety reviews to ensure compliance with requirements. Of most importance to everyone involved in the program was an increased awareness of the high safety quality required to send people to the Moon and back.

Space Shuttle. The Space Shuttle launch vehicle was highly integrated and employed a stage-and-a-third parallel-burn philosophy. In this configuration, the Orbiter vehicle and crew were much closer to the source of explosive yield of fire and overpressure than in the in-line series burn configurations used on the Mercury, Gemini, and Apollo launch systems. Thus, the considerations for crew safety were a tremendous challenge over previous programs. The most significant challenge was how to address the issue of aborts during first stage. To enable the possible consideration of crew escape, crew ejection, pod ejection, or Orbiter separation and fly-away, a method for thrust termination of the solid rocket boosters (SRBs) had to be developed.

To separate from a vehicle thrusting in excess of 6.4 million pounds required the capability to shut down the solid boosters and main liquid engines. Shutting down the liquid engines was a proven technology, but extinguishing an SRB was not. Various concepts were examined for thrust termination on the SRBs. One concept was to pyrotechnically blow out the head end of the booster and neutralize thrust; another concept was to sever the nozzle to accomplish the same purpose. Either approach had three major concerns or significant design challenges. As a result, the decision was made that the additional safety risks and design complexities introduced by thrust termination were of greater concern than the presumed low failure rates of solid motors. For those areas considered "high" risk, more stringent design requirements were derived to build in greater reliability for the Space Shuttle boosters. Targeted areas were case structural design factors of safety, case insulation, and segment seals.

In summary, crew safety design decisions vary as a *function of program*, with decisions made based on the integrated view of program requirements, physical constraints, system performance, and system cost and benefit. Mercury and Gemini Program managers accepted the reliability of the launcher and designed additional safety via capsule or crew ejection. Apollo Program managers employed the same crew ejection approach but designed in additional safety measures into the launcher. The Shuttle used a historical performance database to improve safety design and certified the vehicle to be human-rated with no first stage abort capability.

2.1.2 Implementation Methods Vary by Mission Phase

Apollo. Apollo redundancy and abort criteria depended on mission phase. During lunar descent, the crew had the option to abort the landing by separating the descent stage and returning to lunar orbit with the

ascent stage. Once on the lunar surface, however, the ascent vehicle had no abort capability and no engine-out capability. The cost to provide lunar ascent abort capability was judged to be prohibitive. Engineering and program judgment concluded that the benefit was worth the cost. Therefore, Program managers instead decided that an acceptable level of reliability could be achieved by using simple systems of proven reliability (such as a pressure-fed engine and hypergolic propellants) and by performing substantial ground tests to certify reliability. Conversely, the cis-lunar trajectory sacrificed performance to provide maximum abort capability (free return).

Space Shuttle. The Space Shuttle has the capability for launch abort throughout all mission phases presuming nominal SRB thrust. There is no abort option for the loss of SRB function. Again, as discussed in the previous section, probabilistic risk assessments were made during the definition phase of the Program to target problem areas and increase design margins. Thus, to provide the required safety within physical and cost constraints, various implementation approaches have been used in different phases of the same Program. Again, the focus is not on implementation approach, such as crew ejection, but on a system-level integrated methodology that considers cost, schedule, performance, risk, and benefits.

2.1.3 Human Safety Approach Is Dictated by Risk versus Benefit of the Mission

The historical approach has always been a carefully considered balance among cost, schedule, performance, and safety risk for the return benefit. No single implementation option or design approach can be recommended as the "safe" option or approach. Different implementations and approaches were used in different programs as well as in different phases of a program. In all cases, methodologies or processes, or both, were employed that considered all issues of cost, performance, schedule, and safety for the return value of the mission. Safety, which was always a primary consideration in all programs, was combined with oversight approaches to ensure safety through instituting a substantial verification, validation, and certification program.

2.2 Historical Perspective of Human Performance

Human performance has been a growing element of spaceflight since the first Mercury launch of a crew member into suborbital trajectory. As the complexity of the missions, and the spacecraft designed and developed to support those missions, has grown over the years, the participation of crew members in those missions has likewise had to increase to meet operational goals and objectives. If viewed as an integrated system, the launch vehicle, the flight module, the recovery system, and the human participants are inextricably linked in a common unit. The following addresses the necessity of including the human element in this equation.

Numerous instances are available within the history of the space program where the presence of crew members has led directly to the recovery of a mission or saving of a spacecraft that might otherwise have been lost. Gemini 8 and Apollo 13 are well-publicized examples. As the space program evolves further, the role of human crew members will become more complex and interactive with the evolving technology used to develop spacecraft and ancillary equipment. To this end, the application of human engineering is essential during the development and acquisition of systems, equipment, software, procedures, and facilities to achieve effective integration of the human element into system performance. To fulfill this requirement, NASA-STD-3000, "Man-Systems Integration Standards," has been developed to be used as a programmatically applicable document to human-rated systems.

NASA-STD-3000 is designed to be tailored to any given program that uses a human crew in a flight vehicle. Currently, program-specific volumes have been developed for the Space Station Program

(Volume IV). These documents address the spaceflight specific factors within the human engineering discipline by systematically treating chapters on:

- Anthropometry and biomechanics
- Human performance capabilities
- Natural and induced environments
- Crew safety
- Health management
- Architecture
- Workstations
- Activity centers
- Hardware and equipment
- Maintainability
- Facility management
- Extravehicular activity

Additionally, NASA Safety Standard NSS 1740.XX, the "Human Engineering Handbook for Safety Assurance," is being revised to address the need for human engineering application to future programs and recognize that the human element early on in program development is an essential task.

2.3 Historical Perspective of Human Health Management and Care

The goals of space medicine are to sustain life and maintain productive human function throughout all phases of spaceflight. The discovery of space motion sickness, dramatic vascular fluid shifts, hematopoistic abnormalities, and postflight gravitational intolerance as distinct physiological entities and the demonstration of human survivability in a space environment occurred as a direct extension of these goals during Project Mercury.

The Gemini Program further elucidated cardiovascular, hematological, and musculoskeletal changes associated with extended spaceflight. In addition, Gemini established our understanding of the physiological principles associated with extravehicular activity. The Apollo Program took mankind to the Moon. Apollo established the physiological foundation for Space Shuttle Orbiter (SSO) missions through its study of spaceflight durations comparable to those of the Orbiter. These missions also demonstrated that many in-flight medical conditions could be safely diagnosed and treated, thus confirming that interplanetary missions were feasible.

The Skylab Program studied habitability and physiological adaptation problems associated with long-duration spaceflight. Significant countermeasures research including human-rating of the lower body negative pressure suit was first accomplished aboard Skylab. Manual correction of complex electromechanical faults by Skylab crews reaffirmed the need for a human presence aboard subsequent spaceflights. To accomplish this, the need for continued biomedical research was established.

Skylab and the SSO have provided us with a plethora of biomedical data and spin-off technology. These data are currently reflected in the SSO Aeromedical Flight Rules and the Medical Operations Requirements Document (MORD). Critical issues contained in the MORD concerning preflight and postflight training, safety, countermeasures, emergency medical services, rescue operations, and medical evacuation have contributed directly to continued crew health and mission success.

Flight aboard the International Space Station will herald a new era in biomedical research. Space medicine experiments on this platform will allow for exhaustive studies of physiological and psychological changes associated with ultralong-duration spaceflight and the development of effective countermeasures. The data from these studies will allow for the human-rating of interplanetary missions of the future.

3. The Human-Rating Process Is Defined

3.1 Research and Findings

The conventional historical human-rating implementation approaches defined in Table 1 were extracted from applicable NASA Management Instructions (NMIs), NASA reports, and alternative approaches used by other industries. In these, it was concluded that there were no "standard" implementation methods for human-rating from the standpoint of factors of safety, levels of redundancy, etc. These types of methods were found to be mission-dependent and always varied between and within programs with no commonality in application. The research and development efforts, however, did yield two common denominators.

Table 1.
Human-Rating Implementation Approaches

- Design Factors of safety
- Reliability
- Failure Tolerance
- System Health Monitoring
- Emergency Detection
- Crew Escape
- Test and Verification
- Effects of Human Interaction W/System
- Effects of Environment Caused by Human Presence

These items were not "methods" of human-rating, but were specific, and variable, "implementations" that were determined to be appropriate, for each specific application, through a management process that evaluated risk, cost, schedule, and performance.

The first common denominator was that the items listed in Table 1 were not fundamental "*truths*" that were applicable in every case, but instead were *solutions* to a more complex question. The actual human-rating "*implementations*" used were collections of analytical and management processes that always evaluated risk, cost, schedule, and performance in some integrated procedure that varied between programs, within programs, and within mission phases of a program. The graphic in Figure 1 is an attempt to illustrate these points.

The second common denominator was that human-rating consists of more than crew safety. Human-rating has three unique (as compared to unmanned vehicles) sets of requirements that are the primary drivers of system designs: human safety, human performance, and human health management and care. Repositories for these three sets of requirements are identified in Figure 2.

The relationship between human-rating a vehicle or habitat for safety and the requirements for human performance and health management and care is not always clear. One relationship is through the mass assumed for a crew carrier. There are constraints on volume, crew equipment, and support equipment required to ensure a healthy, high-performing crew. Another constraint is that the launch vehicle dynamic parameters must be within crew health and performance boundaries. Finally, there is a relationship through the crew interface with the system. For example, is the mass that the launcher delivers to orbit sufficient to provide the minimum requirements for human health and performance? Are the steady-state and dynamic acceleration loads within human performance requirements? Are the off-nominal performance characteristics of the system within human limits for emergency response?

These findings led to the following characterization of human-rating:

> **Human-rating is the *process* of satisfying the mutual constraints of cost, schedule, performance, risk, and benefit while addressing the requirements for human safety, human performance, and human health management and care.**

3.2 Supporting Definitions

A structured *human-rating process* is always established for all applicable NASA programs and is executed for the complete life cycle of the program. Approval of the human-rating process is normally accomplished as an integral part of the program process defined in NMI 7120.4 and in NASA Handbook (NHB) 7120.5. This *human-rating process* has evolved to consider the requirements for human safety,

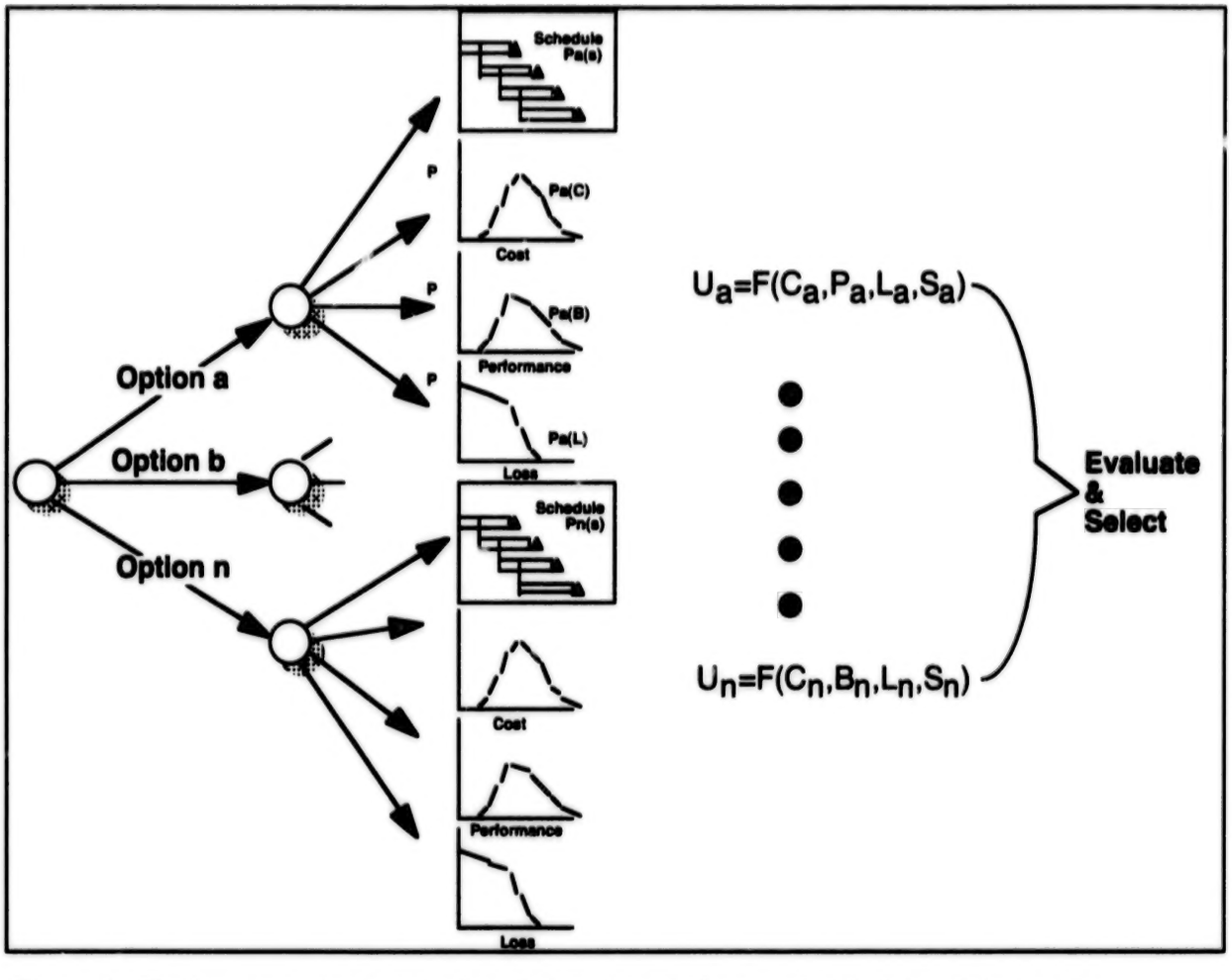

Figure 1. The human-rating process is an integral part of a complex decision. Selecting the appropriate option for human-rating a space system is not as simple as mandating crew escape or quad-redundancy. While in many cases these have been the correct implementation options, sometimes cost, schedule, and performance drive the program to make alternative decisions to achieve the same level of human-rating.

human performance (nominal and degraded states of operation, and human health management and care. The process provides a continuous tracking method for recording system performance against three human-rating elements.

Human safety is the measurement of risk of injury to, or loss of life of, any of the spaceflight personnel. Injury includes injury as a direct result of the space mission as well as long-term effects owing to exposure to the total mission environment.

A safety program conforming to the constraints specified in NASA NHB 1700.1 (V-1B), "NASA Basic Safety Manual" is developed and tailored to the needs of the human-rated space system. The human safety program normally implements a process for risk identification, risk reduction, risk control, risk visibility, and program manager's risk acceptance. The process may use qualitative or quantitative methods, or both, to assess the risk to human safety. Generally, qualitative methods have been used. Sometimes quantitative methods, such as relative probabilistic risk assessment, have been used to resolve critical trade issues in which alternative choices impact system safety.

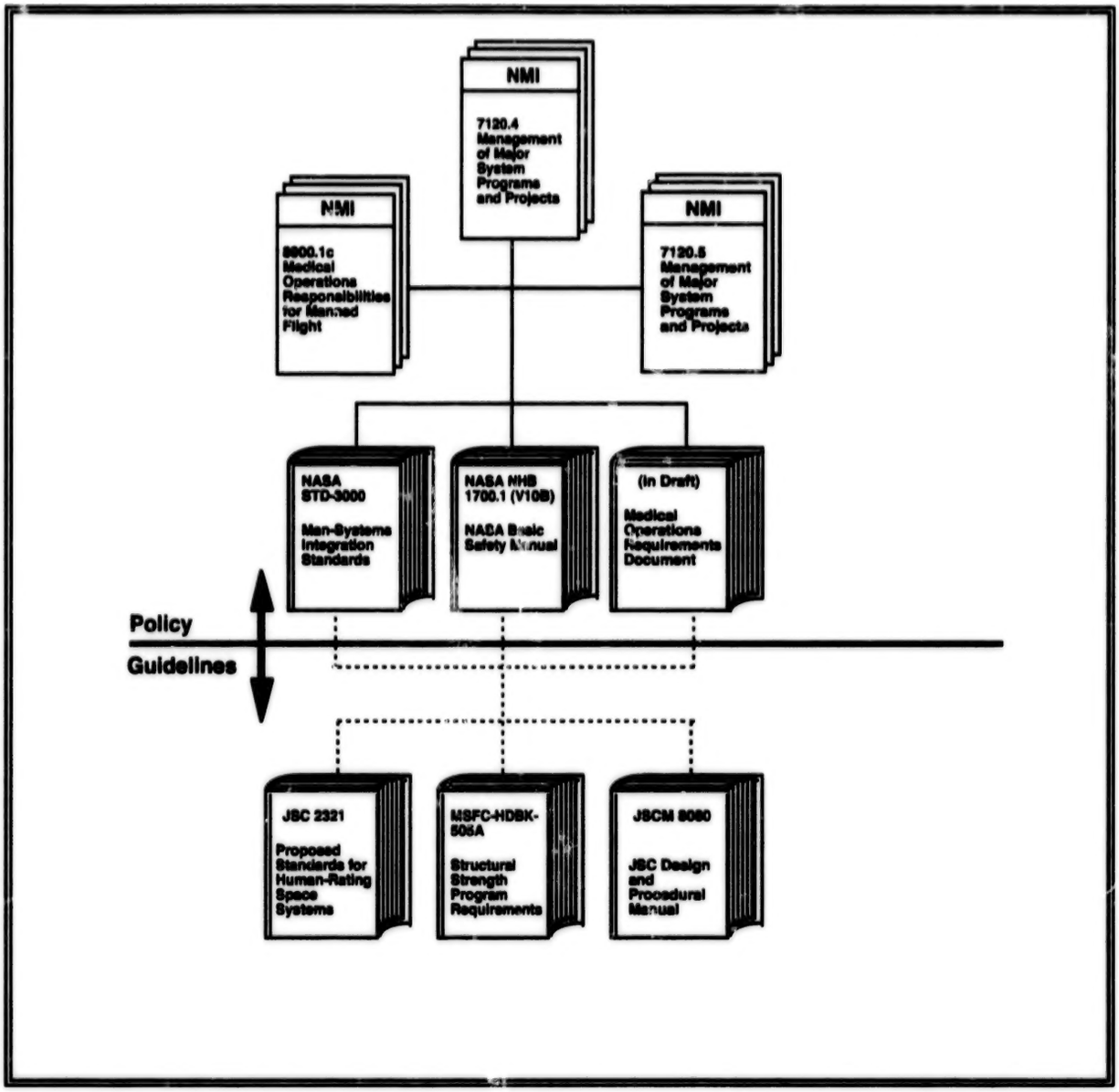

Figure 2. Repository of the historical basis for human-rating. NASA has recorded its experiences in human-rating in a collection of documents and management instructions. This repository contains policies to establish the human-rating processes as well as to recommend implementation approaches.

Human performance is the physical and mental action required of a crew to accomplish mission goals. This includes the interaction of crew members with equipment, computers, procedures, training material, the environment, and other humans. Human performance issues are considered in all phases of a program, including both nominal and program-defined contingency operations. Nominal operation provides an environment that ensures a highly efficient, productive, and healthy crew who are capable of safely executing all mission objectives. Elements affecting the body and mind are designed to be compatible with the human capabilities and limitations to ensure that mission goals are achieved. Measurement of human performance against established criteria is accomplished to allow mission goals to be designed and modified as required to ensure their successful completion.

Human health management and care is that set of activities, procedures, and systems that provide environmental monitoring and crew health assessment, health maintenance and countermeasures, and medical intervention to diagnose and treat injury and illness. Human health management and care issues are considered in all phases of the program. The human-rating process ensures that systems, procedures, training, and protocols appropriately address issues of environmental monitoring and individual health assessment, health maintenance and countermeasures, and medical diagnosis and treatment of injury and sickness. These issues are assessed and measured against appropriate mission risks for each NASA space system.

4. Conclusions and Recommendations

The committee concluded that there were no "standard" implementation methods for human-rating from the standpoint of factors of safety, levels of redundancy, etc. These types of methods were found to be mission-dependent and always varied between and within programs with no commonality in application.

The historical human-rating methods used for space vehicles were collections of analytical and management processes that always evaluated risk, benefit, cost, schedule, and performance in some integrated procedure. The actual top-level requirements for human-rating have remained relatively constant over time. Those requirements are always evaluated as part of an integrated assessment that includes performance, cost, and schedule. This approach has successfully been employed to allow creativity and innovation to direct the program toward a system that is safe, effective, and viable.

The committee recommends that the definition of human-rating be the following:

> A process that satisfies the constraints of cost, schedule, performance, risk, and benefit while addressing the three requirements of human safety, human performance, and human health management and care.

5. References

The following references collect additional historical human-rating details at the implementation level. They are useful specific guidelines in regards to factors of safety, fault tolerance, crew escape, and emergency detect system.

- NASA NHB 1700.1 (V1-B) "NASA Basic Safety Manual"
- NMI 8900.1c, "Medical Operations Responsibilities for Manned Space Flight"
- JSC 13956, "Medical Operations Requirements Document, Revisions"
- NASA STD 3000, "Man-Systems Integration Standards"
- NMI 7120.4, "Management of Major System Programs and Projects"
- NHB 7120.5, "Management of Major System Programs and Projects"
- MSFC-HDBK-505A, "Structural Strength Program Requirements"
- JSC 23211, "Proposed Standards for Human-rating Space Systems"
- JSCM 8080, "JSC Design and Procedural Standards Manual"
- "A Flight Test Challenge: Aeroassist for Reusable, Space Based Transportation," Robert C. Reid

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing the burden, to Washington Headquarters Services, Directorate for information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 1995	NASA Special Publication

4. TITLE AND SUBTITLE

A Perspective On the Human-Rating Process of U.S. Spacecraft: Both Past and Present

5. FUNDING NUMBERS

6. AUTHOR(S)

George A. Zupp, Jr., Editor

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Lyndon B. Johnson Space Center
Structures and Mechanics Division
Houston, Texas 77058

8. PERFORMING ORGANIZATION REPORT NUMBERS

S-798

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

SP-6104

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified/Unlimited
Available from the NASA Center for AeroSpace Information (CASI)
800 Elkridge Landing Road
Linthicum Heights, MD 21090-2934
(301) 621-0390 Subject category: 18

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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14. SUBJECT TERMS	15. NUMBER OF PAGES
human factors engineering, man machine systems, manned spaceflight	14
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unlimited

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std. 239-18
298-102

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DATE

FILMED

JUN 6 1995